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ANALYSIS OF A HELIUM PRESSURANT LOADING SYSTEM FOR A FLUID SUPPLY SYSTEM (FSS)

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AIR FORCE WEAPONS LABORATORY
Air Force Systems Command
Kirtland Air Force Base, NM 87117

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This report describes a model for the analysis of a fluid supply system (FSS) loading system to determine the pressure-, temperature-, and mass-time history of the helium pressurant during loading. The equations developed were coded into a computer program. Sample results are given.

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SECTION I

INTRODUCTION

A gas dynamic laser (GDL) is a combustor-driven device that requires propellants for operation. The propellants are supplied to the combustor by the fluid supply system (FSS).

The FSS is a series of tanks (three propellant tanks and two pressurant tanks), associated plumbing, and a control system to regulate the propellant flow and tank pressures. The propellant tanks are pressurized with a helium pressurant. The helium pressurant supplies the energy for the propellant transport from the tanks to the combustion chamber.

The helium pressurant tanks are pressurized from an ambient, high-pressure helium source tank. The helium from the source tank is pressure controlled to the lower pressure of the pressurant tank and cooled to near liquid nitrogen temperatures by a nitrogen bath heat exchanger. The pressurant tanks are double-wall vacuum jacketed tanks with external cooling coils.

SECTION II

ANALYSIS OF THE FSS LOADING SYSTEM

A schematic of the pressurant loading system is shown in figure 1.

It can be shown that the temperature of the pressurant helium in the FSS at the start of the operation of a GDL should be nearly the same temperature as the propellant it will pressurize for best operation. This procedure reduces the heat and mass transfer between the pressurant and the propellant in the propellant tank. This pressurant temperature condition requires one pressurant tank to be cryogenic (140°R) and the second to be near ambient (400°R).

This report describes the analysis of the pressurant loading system to determine the temperature-, pressure-, and mass-time history of the helium pressurant system.

The pressurant loading of the two tanks can be conducted several ways. These include: (1) simultaneous tank loading (load both tanks at the same time), (2) sequential loading (load one tank, then transfer its contents to the second tank while maintaining the first tank at constant pressure, and (3) individual loading (load each tank independently).

The analysis of the pressurant loading systems was made by taking energy and mass balances around each tank.

Time dependent energy equation:

$$\frac{d}{dt}(m\tilde{e}) - \delta\dot{Q} - \delta\dot{W}_n + \sum_j(\tilde{h}\dot{m})_j - \sum_k(\tilde{h}\dot{m})_k \qquad (1)$$

Time dependent mass equation:

$$\frac{d}{dt}(m) = \sum_j m_j - \sum_k m_k \qquad (2)$$

Heat transfer between the helium and the tank walls was considered. The temperature distribution within the wall was determined from the time dependent heat conduction equation.

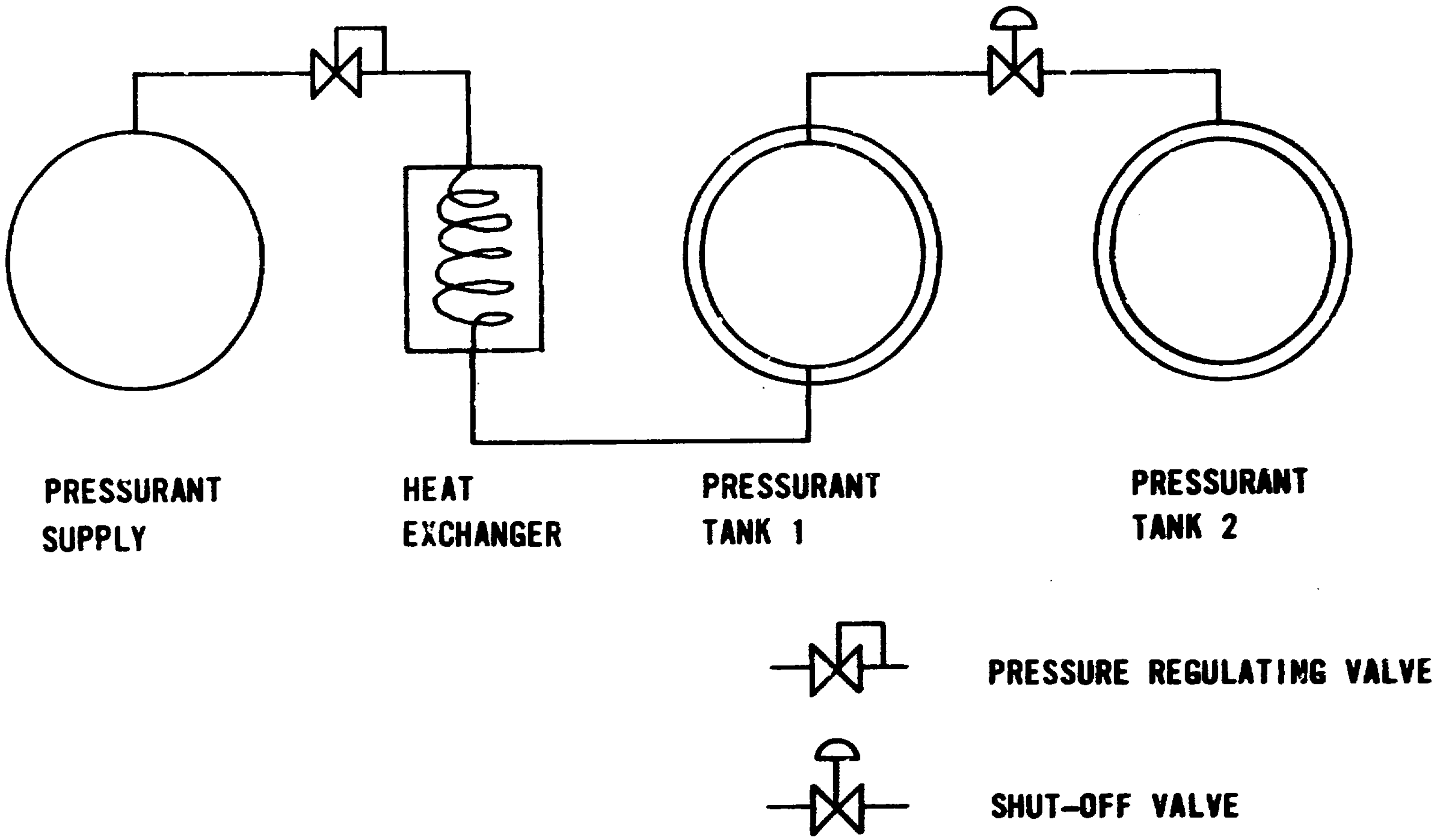

Figure 1. Pressurant Fill Process Schematic

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial \xi^2} \tag{3}$$

The initial and boundary conditions, as well as the additional equations, necessary for solution of the set of differential equations are determined from the constraints imposed on the system.

Several assumptions have been made to simplify the analysis.

1. Instantaneous and homogeneous mixing of any incoming helium streams and the helium contents of the tanks.

2. No energy or pressure losses due to flow-through interconnecting lines.

3. The pressure controllers operate isenthalpicly.

4. The heat exchanger is 100 percent efficient.

5. The cooling coils on the pressurant tanks distribute their effect over the entire surface of the tank, not just point locations.

6. The wall temperature distribution can be approximated by a third order polynomial in the spatial coordinant.

The set of differential equations was evaluated numerically using a modified Adams method as implemented in DIFSUB* on the CDC 6600 at the Air Force Weapons Laboratory, Kirtland AFB, New Mexico. The necessary helium thermodynamic data was supplied by the National Bureau of Standards and is that found in NBS Technical Note 622.**

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SECTION III

SAMPLE RESULTS

Although the set of differential equations could be used to analyze the several different pressurant loading schemes, the most promising scheme appears to be the sequential loading. In this procedure, helium is loaded into one tank with prechilled walls. This tank will be the cryogenic temperature tank. Once the pressure in the cryogenic temperature tank reaches a set value, e.g., the maximum pressure, helium is allowed to flow from the cryogenic temperature tank to the second (ambient temperature) tank. The walls of the ambient temperature tank may or may not be initially at ambient temperatures. Flow into the ambient temperature tank is controlled so that a constant pressure is maintained within the cryogenic temperature tank. During the loading operation, the cooling coil on the cryogenic tank is removing energy from the helium in that tank. Once the maximum pressure within both tanks is reached, the helium flow between the tanks is terminated. The cryogenic temperature tank is cryopumped to its final temperature, where upon the pressurant tank loading is completed.

Figure 2 shows the temperature-time history, figure 3 shows the pressure-time history and figure 4 shows the mass-time history for the two pressurant tanks for a sequential loading procedure.

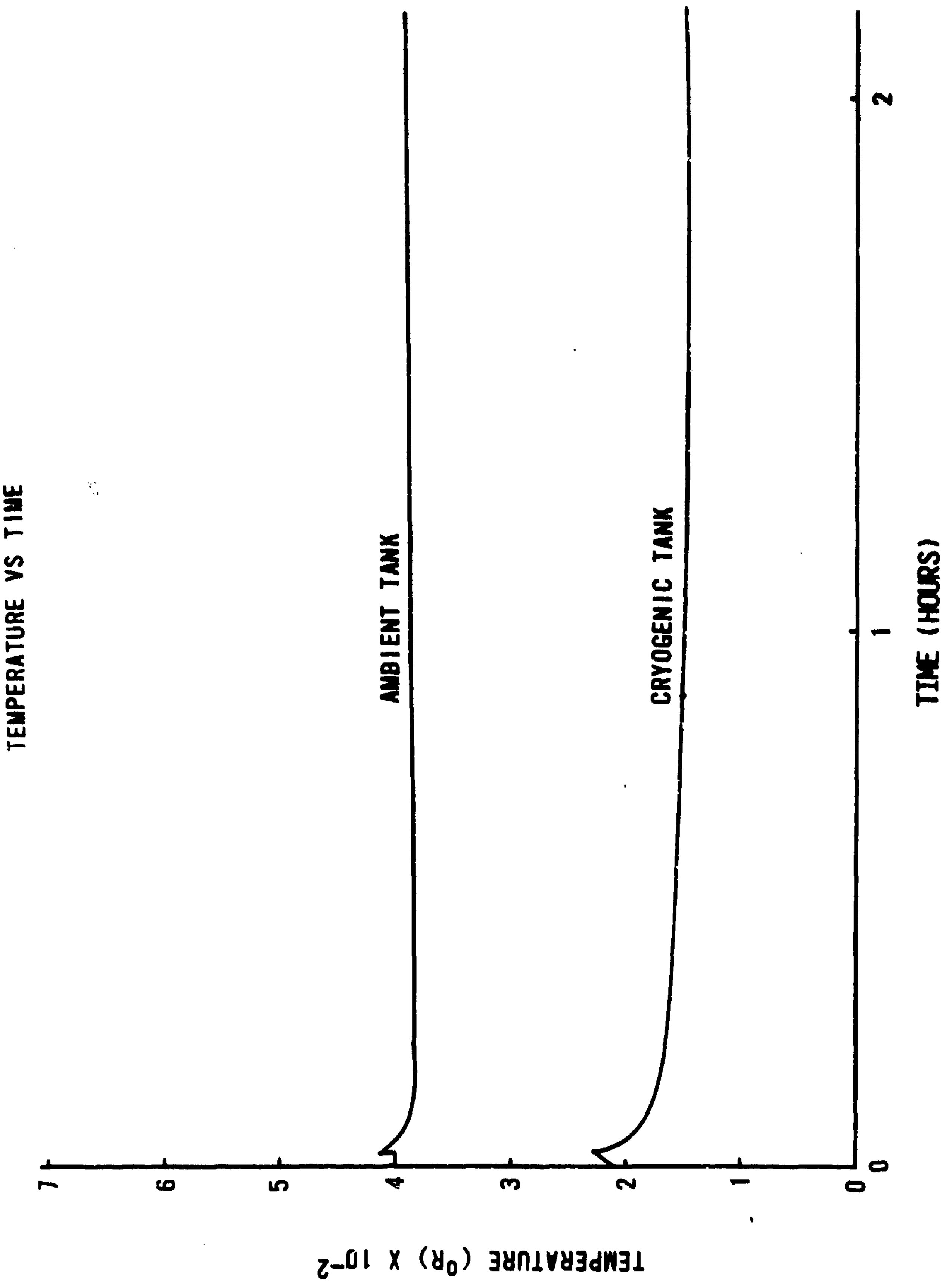

Figure 2. Predicted Temperature History of Pressurant Tank

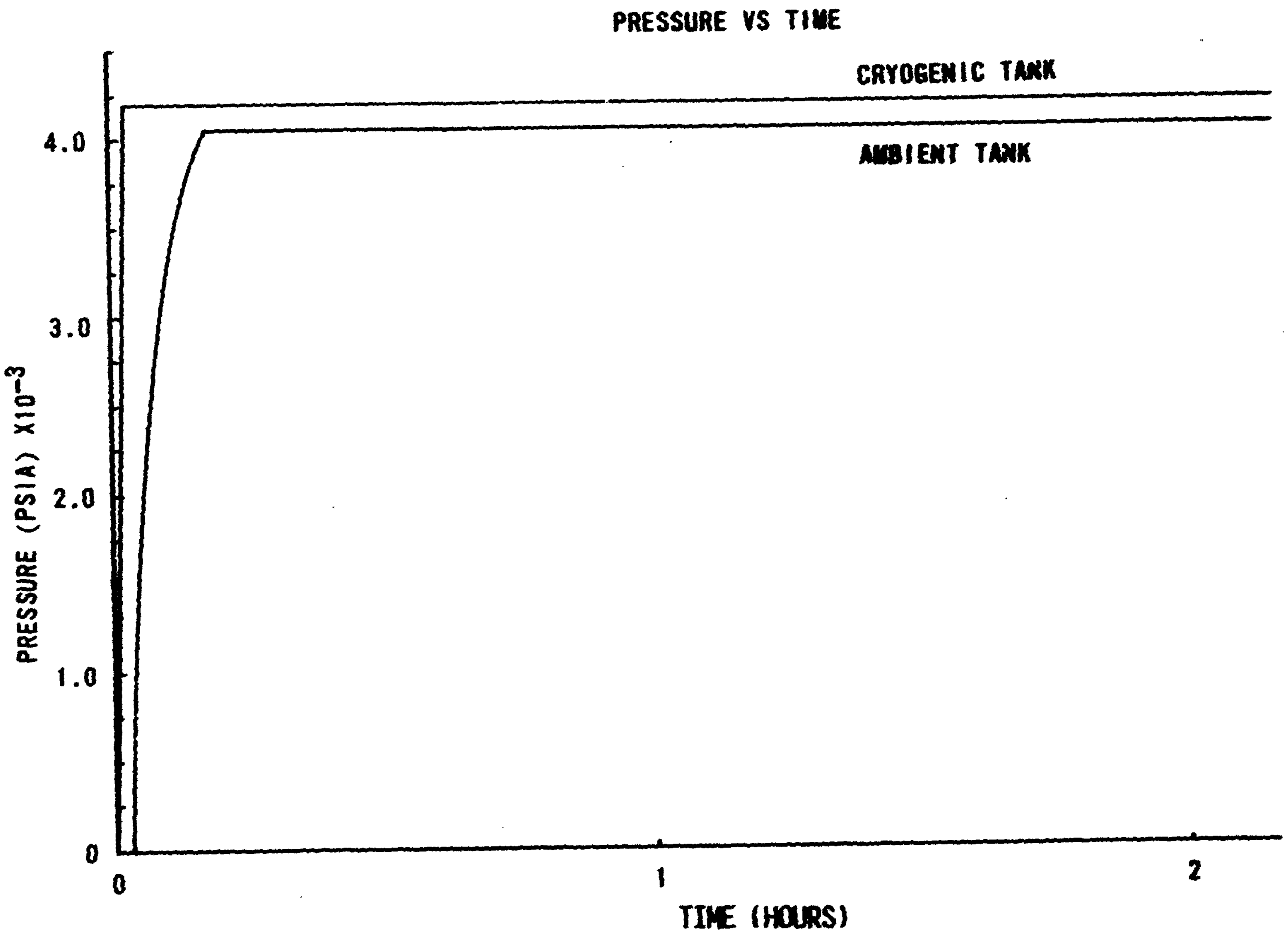

Figure 3. Predicted Pressure History of Pressurant Tank

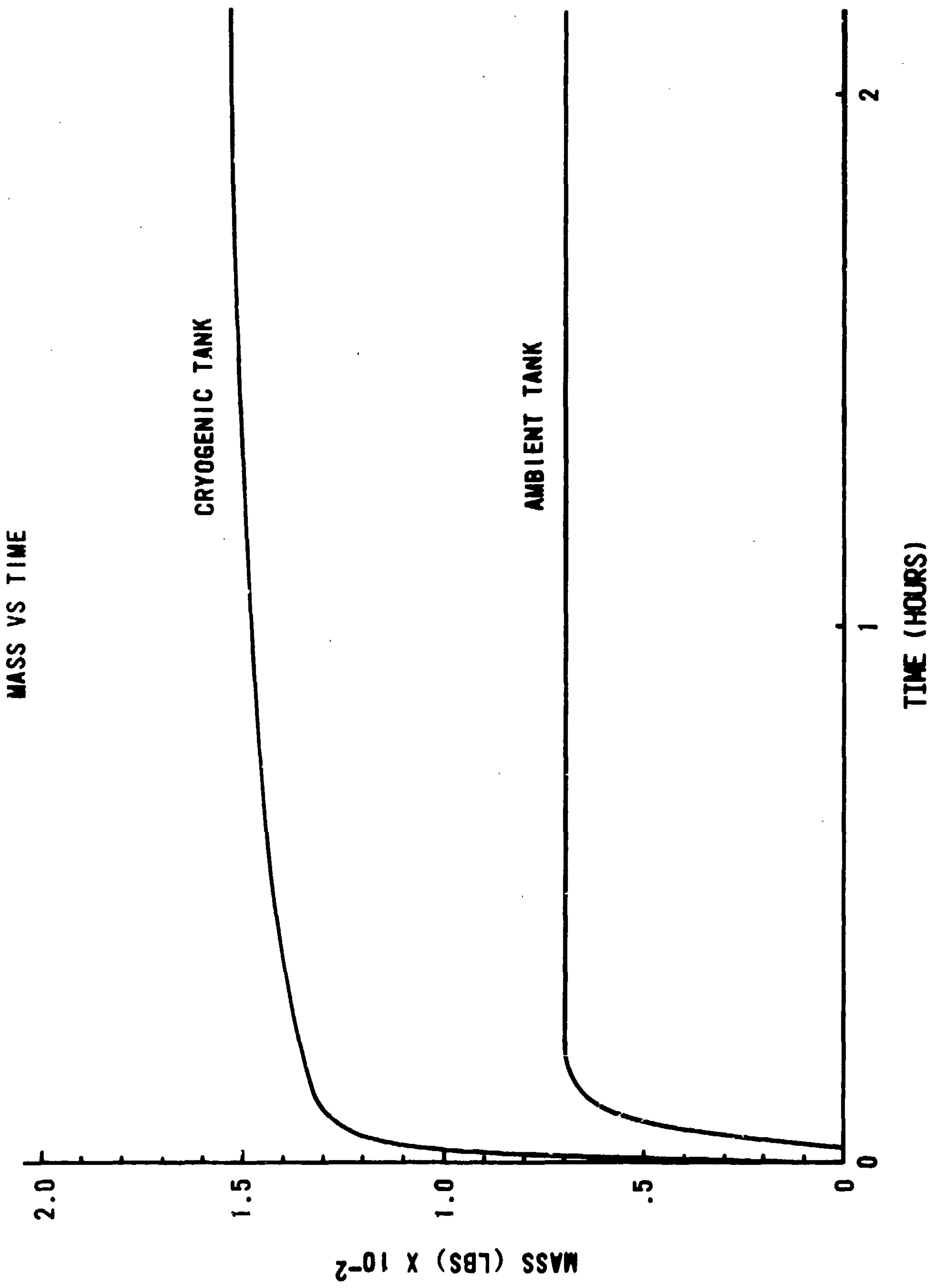

Figure 4. Mass History of Pressurant Tanks

APPENDIX

DEVELOPMENT OF EQUATIONS

$$\frac{d}{dt}(m\tilde{c}) = \delta Q - \delta W_{n} + \sum_{j}(\tilde{h}m)_{j} - \sum_{k}(\tilde{h}m)_{k} \tag{4}$$

$$\frac{dm}{dt} = \sum_{j} m_{j} - \sum_{k} m_{k} \tag{5}$$

Equations (4) and (5) describe the energy and mass time rates of change, respectively, for any control volume i. For clarity the i subscript has been omitted. In addition, two definitions, equations (6) and (7) are presented.

$$H = E + PV \tag{6}$$

$$m = \rho V \tag{7}$$

Equation (6) defines enthalpy; equation (7) defines density. If only internal energy is significant, equation (6) can be rewritten.

$$m\tilde{h} = m\tilde{e} + PV \tag{8}$$

Time derivatives can be taken of equations (8) and (7).

$$\frac{dm}{dt} = \rho\frac{dV}{dt} + \frac{Vd\rho}{dt} \tag{9}$$

$$\frac{md\tilde{h}}{dt} + \frac{\tilde{h}dm}{dt} = \frac{d}{dt}(m\tilde{e}) + \frac{PdV}{dt} + \frac{VdP}{dt} \tag{10}$$

For the analysis, energy and mass balances are taken on the helium within well defined control volumes, i.e., the tanks. Since helium is a pure material and will be only in the gaseous phase, the Gibbs phase rule specifies any intensive property can be determined by two other intensive properties, specifically temperature and pressure. Specific enthalpy and density can, therefore, be expressed as functions of temperature and pressure only.

$$\tilde{h} = \tilde{h}\ (T,\ P) \tag{11}$$

$$\rho = \rho\ (T,\ P) \tag{12}$$

Substituting equations (10) and (11) into (4), substituting equation (12) into (9), and rewriting equation 5, yield the following equations.

$$\left.\frac{m\partial\tilde{h}}{\partial t}\right|_P \frac{dT}{dt} + \left(\left.\frac{m\partial\tilde{h}}{P}\right|_T - V\right)\frac{dP}{dt} = \delta\dot{Q} - \delta W_n + \sum_j (\tilde{h}\dot{m})_j - \sum_k (\tilde{h}\dot{m})_k \tag{13}$$

$$\left.\frac{V\partial\rho}{\partial T}\right|_P \frac{dT}{dt} + \left.\frac{V\partial\rho}{\partial P}\right|_T \frac{dP}{dt} + \frac{\rho dV}{dt} - \frac{dm}{dt} = 0 \tag{14}$$

$$\frac{dm}{dt} = \sum_j n_j - \sum_k \dot{m}_k \tag{15}$$

Equations (13), (14), and (15) form the basis for the analysis of the helium loading system for the FSS. In addition to the three equations, four more relations are required.

$$\frac{dV}{dt} = V'(t) \tag{16}$$

$$\dot{Q} = \dot{Q}(t) \tag{17}$$

$$\dot{W}_n = \dot{W}(t) \tag{18}$$

$$\dot{m} = \dot{m}(t) \tag{19}$$

These four equations are obtained after determing the constraints that are assumed to apply to the system. For the analysis

$$V'(t) = 0$$

$$\dot{W}(t) = 0$$

These conditions are due to the rigid wall construction of the propellant tanks.

$$\dot{m}(t) = \text{arbitrary constant}$$

This condition is dependent upon the capacity of the heat exchanger and is a necessary but arbitrary function for the solution of the system of equations.

Of importance is the heat rate equations for the cryogenic and ambient temperature helium tanks. Since the tank walls are a large thermal mass, heat flux to and from these walls can greatly effect the helium conditions within the tanks.

Heat is assumed to flux through the tank walls due to tank interior and exterior temperature differences. Convective or Newtonian heat transfer is assumed at the tank wall surfaces. Conductive or fourier heat transfer is assumed within the tank wall.

The tanks of the FSS are spherical. Since the tank radius is generally much greater than the tank wall thickness and the heat flux is assumed to be evenly distributed on the tank wall surface, the heat conduction equation can be written approximately in one dimensional cartessian coordinates.

$$\frac{\partial T_w}{\partial t} = \alpha \frac{\partial^2 T_w}{\partial \xi^2} \tag{20}$$

The initial condition is

$$T_w(\xi,0) = T_{wi} \qquad \text{all } \xi \tag{21}$$

The boundary conditions are

$$\frac{\partial T_w}{\partial \xi}(L,t) = \frac{\eta_I}{k}\left(T - T_w(L,t)\right) \qquad t > 0,\ \xi = L \tag{22}$$

$$\frac{\partial T_w}{\partial \xi}(0,t) = \frac{\eta_o}{k}\left(T_w(0,t) - T_c\right) \qquad t > 0,\ \xi = 0 \tag{23}$$

The initial and boundary conditions are not homogeneous so an analytic solution by separation of variables is not possible. The wall temperature distribution can be approximated by assuming a polynomial $T_w = P(\xi,t)$ where the coefficients are to be determined. For the analysis a third order polynomial in ξ was assumed.

$$T_w = B\xi^3 + C\xi^2 + D\xi + E' \tag{24}$$

Substituting equation (24) into (22) and (23) lead to two algebraic equations. Substituting equation (24) into (20) and solving for $\xi = 1/3^L$ and $\xi = 2/3^L$ leads to two differential equations for the time rate of change of the coefficients B and C of the form

$$F_1 \frac{\partial B}{\partial t} + F_2 \frac{\partial C}{\partial t} + F_3 \frac{\partial T}{\partial t} + F_4 \frac{\partial T_c}{\partial t} = G \tag{25}$$

$\frac{\partial T}{\partial t}$ is obtained from equations (13) through (15). $\frac{\partial T_c}{\partial t}$, the time rate of change in the coolant temperature has to be approximated.

$$\frac{\partial T_c}{\partial t} = 100\,\frac{L^2}{\alpha}\left(T_c' - T_w\right)$$

This arbitrary approximation assumes that the response of the coolent temperature is 100 times greater than the temperature response of one side of the tank wall to a temperature change to the other side.

Once the temperature distribution is known the heat rate $\delta\dot{Q}$ can be evaluated.

$$\delta\dot{Q} = \eta_I A\left(T - B\xi^3 - C\xi^2 - D\xi - E'\right) \tag{26}$$

Further the heat load on the coolant coil can be evaluated.

$$\dot{Q}_c = \eta_o A \,(E' - T_c) \qquad (27)$$

The heat transfer coefficient η_I was approximated by evaluating the natural convective heat transfer coefficient for a verticle flat plate with a length equal to the tank diameter. The fluid properties were evaluated assuming the pressure to be the maximum and the temperature to be the time-averaged temperature for the helium within the tank.

The heat transfer coefficient η_o was approximated by evaluating the heat transfer coefficient for turbulent flow in tubes, i.e., the cooling coil, for a constant heat flux. The coefficient obtained was then reduced by the ratio of cooling coil shadow area to the total tank area. The fluid properties were evaluated for liquid nitrogen.

ABBREVIATIONS AND SYMBOLS

Variables	Meaning	Units
A	surface area of tank for heat flux	ft^2
B	first coefficient for wall temperature distribution	$°R/ft^3$
C	second coefficient for wall temperature distribution	$°R/ft^2$
D	third coefficient for wall temperature distribution	°R/ft
$\tilde{e}$	specific internal energy	BTU/lb
E	energy	BTU
E'	fourth coefficient for wall temperature distribution	°R
F_1-F_4	function involving the heat transfer coefficients and wall thickness, used in equation (25) to evaluate the wall temperature distribution coefficients	---
G	function involving the thermal diffusivity and wall thickness, used in equation (25) to evaluate the wall temperature distribution coefficients	---
$\tilde{h}$	specific enthalpy	BTU/lb
H	enthalpy	BTU
k	thermal conductivity	BTU/sec-ft-°R
L	wall thickness	ft
m	mass	BTU
$\dot{m}$	mass rate	lbs/sec
P	pressure	psia
$\dot{Q}$	heat rate	BTU/sec
T	helium temperature	°R
T_c	coolant temperature	°R
T_w	wall temperature for equation (21)	°R
t	time	sec
V	volume	ft^3
$\dot{W}_n$	work rate	BTU/sec
α	thermal diffusivity	ft^2/sec

ABBREVIATIONS AND SYMBOLS (cont'd)

Variables	Meaning	Units
η_I	heat transfer coefficient of tank interior wall	BTU/sec-ft^2-°R
η_O	heat transfer coefficient of tank exterior wall	BTU/sec-ft^2-°R
ξ	length along one-dimensional coordinant	ft
ρ	density	lb/ft^3

Subscripts

i	denotes initial conditions
j	denotes flow into a control volume
k	denotes flow out of a control volume
P	denotes constant pressure
T	denotes constant temperature

Symbols

$\sum$	summation
Δ	change in; $\Delta T = T_2 - T_1$
$\frac{d}{dt}$	time derivative
$\frac{\partial}{\partial P}$	partial derivative with respect to pressure
$\frac{\partial}{\partial T}$	partial derivative with respect to temperature
$\frac{\partial}{\partial t}$	partial derivative with respect to time
$\frac{\partial}{\partial \xi}$	partial derivative with respect to one-dimensional coordinate ξ
$\frac{\partial^2}{\partial \xi^2}$	second partial derivative with respect to one-dimensional coordinate ξ